Potential of Carbon Accumulation in No-Till Soils with Intensive Use and Cover Crops in Southern Brazil

Telmo Jorge Carneiro Amado,* Cimélio Bayer, Paulo Cesar Conceição, Evandro Spagnollo,
Ben-Hur Costa de Campos, and Milton da Veiga

ABSTRACT

The area under no-till (NT) in Brazil reached 22 million ha in 2004–2005, of which approximately 45% was located in the southern states. From the 1970s to the mid-1980s, this region was a source of carbon dioxide to the atmosphere due to decrease of soil carbon (C) stocks and high consumption of fuel by intensive tillage. Since then, NT has partially restored the soil C lost and reduced the consumption of fossil fuels. To assess the potential of C accumulation in NT soils, four long-term experiments (7–19 yr) in subtropical soils (Paleudult, Paleudalf, and Hapludox) varying in soil texture (87–760 g kg^{-1} of clay) in agroecologic southern Brazil zones (central region, northwest basaltic plateau in Rio Grande Sul, and west basaltic plateau in Santa Catarina) and with different cropping systems (soybean and maize) were investigated. The lability of soil organic matter (SOM) was calculated as the ratio of total organic carbon (TOC) to particulate organic carbon (POC), and the role of physical protection on stability of SOM was evaluated. In general, TOC and POC stocks in native grass correlated closely with clay content. Conversely, there was no clear effect of soil texture on C accumulation rates in NT soils, which ranged from 0.12 to 0.59 Mg ha^{-1} yr^{-1}. The C accumulation was higher in NT than in conventional-till (CT) soils. The legume cover crops pigeon pea [*Cajanus cajan* (L.) Millsp] and velvet beans (*Stizolobium cinereum* Piper & Tracy) in NT maize cropping systems had the highest C accumulation rates (0.38–0.59 Mg ha^{-1} yr^{-1}). The intensive cropping systems also were effective in increasing the C accumulation rates in NT soils (0.25–0.34 Mg ha^{-1} yr^{-1}) when compared to the double-crop system used by farmers. These results stress the role of N fixation in improving the tropical and subtropical cropping systems. The physical protection of SOM within soil aggregates was an important mechanism of C accumulation in the sandy clay loam Paleudult under NT. The cropping system and NT effects on C stocks were attributed to an increase in the lability of SOM, as evidenced by the higher POC to TOC ratio, which is very important to C and energy flux through the soil.

SOUTHERN BRAZIL is an important agriculture region, mainly due to the production of soybean [*Glycine max* (L.) Merr.], maize (*Zea mays* L.), rice (*Oryza sativa* L.), sorghum [*Sorghum bicolor* (L.) Moench], wheat (*Triticum aestivum* L.), and black beans (*Phaseolus vulgaris* L). This region was the origin of Brazilian no-till (NT) farming in the early 1970s. At that time, NT was introduced to control the severe erosion widespread in agricultural soils.

Southern Brazil had a very quick shift in land use from forest and native grassland to agriculture. In 1969, the cropland area in the state of Rio Grande do Sul was 0.8 million ha, while it reached 4 million ha in 1977 (Mielniczuk, 2003). During that time, southern Brazil cropland relied on a soil management system based on intensive tillage (two plows + four to six disks per year), soybean–wheat double-cropping system, wheat straw burning, and large areas with winter fallow. This soil management system caused severe soil degradation due to widespread erosion. In the 1970s, it was estimated that for each 1 kg of soybean harvested in southern Brazil, approximately 10 kg of fertile topsoil were eroded (Gianluppi et al., 1979; Mielniczuk, 2003).

To counteract this unsustainable management, the farmers of southern Brazil started to adopt NT practices. Farmers adapted NT to tropical and subtropical environments mainly by increasing the amount of straw by using winter cover crops and summer crop rotation to compensate for the rapid residue decomposition. The farmers called this system "NT in the straw" due to the high amount of mulch left on the soil surface at seeding time. In the mid-1980s, NT was rapidly adopted in southern Brazil, achieving 80% of total cropland (approximately 10 million ha) in 2004–2005. From the 1970s to the mid-1980s, this region was estimated to be a source of carbon dioxide to the atmosphere, but it has transformed since then into a major C sink thanks to the adoption of NT and other soil conservation practices (Mielniczuk et al., 2003; Bayer et al., 2006b).

In addition to favorable conditions for biological decomposition of SOM, southern Brazil has a well-distributed rainfall pattern through the year allowing for the development of intensive cropping systems, with three or even four crops per year, that can result in high addition of crop residues to the soil surface (Mielniczuk et al., 2003; Bayer et al., 2006b). These systems increase the input of biomass C to the soil and, consequently, lead to the accumulation of C in soils under conservation tillage systems as verified in tropical Cerrado (Bayer et al., 2000a, 2006b; Amado et al., 2001) and temperate soils (Lal et al., 1999).

No-till improves physical protection of SOM within soil aggregates. Particulate fractions of SOM occluded into soil aggregates have longer turnover times than free

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T.J.C. Amado, Department of Soil Science, Federal University of Santa Maria, Zip Code 97119-900, Santa Maria, RS, Brazil. C. Bayer and P.C. Conceição, Department of Soil Science, Federal University of Rio Grande do Sul, Zip Code 90001-970, Porto Alegre, RS, Brazil. E. Spagnollo and M. da Veiga, Agricultural Research and Rural Extension Organization for the State of Santa Catarina (Epagri), Zip Code 88034-901, Florianópolis, SC, Brazil. B.C. Campos, Center of Experimentation and Research Fundacep, 98100-970, Cruz Alta, RS, Brazil. Received 10 June 2005. *Corresponding author (tamado@smail.ufsm.br).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: CPI, carbon pool index; CT, conventional tillage; NT, no tillage; POC, particulate organic carbon; POCPI, particulate organic carbon pool index; RT, reduced tillage; SOM, soil organic matter; TLCC, tropical legume cover crop; TOC, total organic carbon.

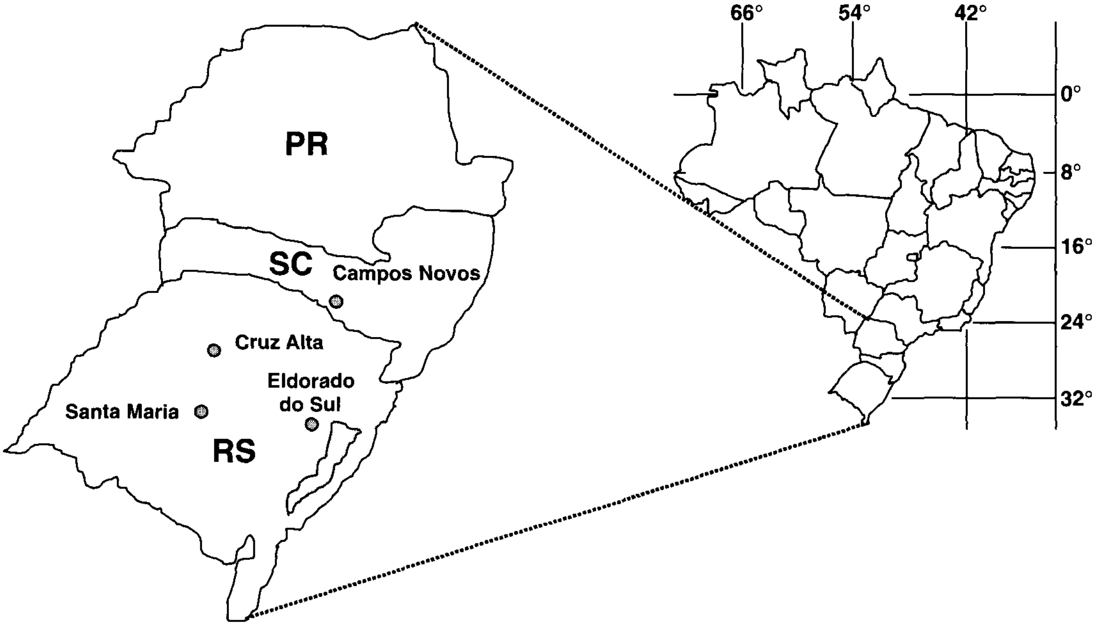

Fig. 1. Map of southern Brazil and the localization of the experimental areas.

fractions (Feller and Beare, 1997; Lal et al., 1999; Six et al., 1998, 1999, 2000). However, few studies have been performed in soils from southern Brazil. Variable charge minerals could improve this mechanism of SOM stabilization and as a consequence contribute to C accumulation in NT soils (Parfitt et al., 1997; Hassink and Whitmore, 1997; Balesdent et al., 2000; Baldock and Skjemstad, 2000). In general, the less oxidative environment in NT soils increases the lability of SOM, as evidenced by spectroscopic techniques (Bayer et al., 2000a, 2001) and by the ratio between labile and nonlabile pools of SOM (Diekow et al., 2005b).

In this study four of the oldest NT experiments in the southern Brazil were sampled to evaluate the effect of crop rotation and cover crops on the enhancing the potential of organic C accumulation and the lability of SOM in soils with different texture and mineralogy. Further, the physical fractionation of SOM was performed in a sandy clay loam soil to evaluate a magnitude of the physical protection as a mechanism of SOM stabilization in NT soils.

MATERIAL AND METHODS

Field Sites

Four long-term soil management experiments located in Rio Grande do Sul (RS) and Santa Catarina (SC) states, southern Brazil, were used in this research (Fig. 1). The first study began in an area under native grass, while the other experimental areas had a previous history of CT for 13 to 20 yr. These experiments were performed from 7 to 19 yr considering the period from their start until the soil sampling for this study.

The first experiment was performed at the Federal University of Santa Maria (UFSM) in Santa Maria (RS) for 10 yr (1991–2001). The soil, a Typic Paleudalf (Soil Survey Staff, 1999), has a sandy loam A horizon with a clay content of 87 g kg^{-1}. This soil is referred herein as sandy loam Paleudalf (Table 1). The climatic classification is wet subtropic Cfa in Koeppen classification (Koeppen, 1948). The average precipitation is 1769 mm yr^{-1}, without dry season. The average annual temperature is 19.3°C. The experimental design is a randomized block with 3.5- × 22-m plots and two replications. The treatments selected were the following: (i) bare soil, (ii) winter fallow–maize, (iii) ryegrass (*Lolium multiflorum* Lam.)–maize, (iv) velvet beans–maize denominated as tropical legume cover crop (TLCC), and (v) native grass. The last treatment (v) was kept undisturbed, without the presence of animals, as a reference treatment. The maize was fertilized with 120 kg ha^{-1} of N as urea, except the fourth treatment that received 60 kg ha^{-1}. The experiment was amended with lime and fertilized with phosphorus and potassium following soil analysis. Bayer et al. (2006a) showed experimental data for this experiment.

The second experiment was performed from 1985 to 2001 at the Federal University of Rio Grande do Sul (UFRGS) in Eldorado do Sul (RS). The soil is a Paleudult (Soil Survey Staff, 1999) with a sandy clay loam A horizon with a clay content of 220 g kg^{-1}. It is designated here as sandy clay loam

Table 1. Main soil characteristics at the beginning of the experiments in southern Brazil.†

Location	Soil classification	Coordinates	Elevation	Particle size			pH (water)	P	K
				Clay	Silt	Sand			
			m	g kg^{-1}				mg kg^{-1}	
Santa Maria	**sandy loam Paleudalf**	**29°45′ S, 53°42′ W**	**96**	**87**	**253**	**660**	**4.5**	**1.8**	**33**
Eldorado Sul	**sandy clay loam Paleudult**	**30°50′ S, 51°38′ W**	**96**	**220**	**240**	**540**	**4.5**	**9.0**	**78**
Cruz Alta	**clay Hapludox**	**28°36′ S, 53°40′ W**	**435**	**570**	**120**	**310**	**4.5**	**19.0**	**82**
Campos Novos	**high clay Hapludox**	**27°24′ S, 51°13′ W**	**960**	**760**	**90**	**150**	**5.6**	**3.0**	**100**

† Adapted from Conceição (2002), Spagnollo (2004), and Campos (2005).

Paleudult. The climatic classification is wet subtropic Cfa in Koeppen classification (Koeppen, 1948). The average precipitation is 1440 mm yr^{-1}, without dry season. The average annual temperature is 19.4°C. Experimental design is a randomized block with 5- × 10-m plots and three replications. The treatments selected were: (i) black oat (*Avena strigosa* Schreber)–maize under CT (CT = plow + two disks) without mineral N fertilization, (ii) black oat–maize under CT with N fertilization, (iii) black oat–maize under reduced tillage (RT) (chisel) with N fertilization, (iv) black oat–maize under NT with N fertilization, (v) black oat + common vetch [*Vicia sativa* (L.) Walp.]–maize + cowpea [*Vigna unguiculata* (L.) Walp] under NT with N fertilization, designated as Intensive Cropping System I, (vi) pigeon pea–maize under NT with N fertilization, designated as tropical legume cover crop (TLCC), and (vii) native grass. The N fertilization (average of 144 kg ha^{-1} of N) was urea split during the maize growing season. The experiment was amended with lime and fertilized with phosphorus and potassium following soil analysis. Bayer et al. (2000b) and Lovato et al. (2004) reported the experimental data for this field experiment.

The third experiment was performed at the Center of Experimentation and Research Fundacep in Cruz Alta (RS) for 19 yr (1985–2004). The soil is a clay Rhodic Hapludox with a clay content of 570 g kg^{-1} in its upper horizon. It is referred here as a clay Hapludox. The average precipitation is 1727 mm yr^{-1}, without dry season. The average annual temperature is 19.2°C. The climatic classification is wet subtropic Cfa in Koeppen classification (Koeppen, 1948). The experiment was performed in 60- × 40-m plots, which were split in three replications of 30 × 13.3 m to soil sampling. The experimental design is a randomized block, considering the subsamples in the plots as replications. The treatments selected were: (i) wheat–soybean under CT, (ii) wheat–soybean under NT, (iii) black oat–soybean–black oat + vetch–maize–radish oil (*Raphanus sativus* L.)–wheat–soybean, designated as Intensive Cropping System II under CT, (iv) Intensive Cropping System II under NT, and (v) native grass. The experiment was amended with lime and fertilized with N, phosphorus, and potassium following soil analysis. Campos et al. (1995) reported results for this field experiment.

The fourth experiment was performed at the Epagri Experimental Station in Campos Novos (SC) for 7 yr (1994–2001). The soil is a clay Hapludox with a clay content of 760 g kg^{-1} in its upper horizon. The soil is referred herein as a high clay Hapludox. The average precipitation is 1964 mm yr^{-1}, without dry season. The average annual temperature is 16.5°C. The climatic classification is wet temperate Cfb in Koeppen classification (Koeppen, 1948). The experimental design is a randomized block with 6- × 6-m plot size and three replicates. The treatments selected were: (i) triticale (*Triticosecale* spp. Wittm)–rye (*Secale cereale* L.)–soybean–common vetch–maize–black oat–black bean–buckwheat (*Fagopyrum esculentum* Moench) or radish oil, designated as Intensive Cropping System III, with residues removed under CT, (ii) Intensive Cropping System III under CT, (iii) Intensive Cropping System III under NT, and (iv) native grass. The experiment was fertilized with N, phosphorus, and potassium following soil analysis. Veiga et al. (2000) showed the experimental data of this field.

Soil Sampling

Soil samples for organic C analysis were manually collected in the following depth increments: 0 to 2.5, 2.5 to 5.0, 5.0 to 7.5, 7.5 to 10.0, 10.0 to 15.0, and 15.0 to 20.0 cm. Soil samples were air dried at room temperature, crushed with a wood roll to pass through a 2-mm open mesh sieve, and stored in plastic pots. Only the results from 0- to 5- and 0- to 20-cm layers will be presented in this paper.

Soil sampling to densimetric fractionation of SOM was performed only at the 0- to 5-cm depth. The soil was sampled in cores, manually disturbed to pass through a 9.51-mm open mesh sieve, air dried, and stored in plastic pots.

Analysis

Total Organic Carbon

The TOC in the first two sites was determined through the Walkley–Black dichromate oxidation method with external heating (Walkley and Black, 1947), while in the third and fourth sites the Mebius modified method (Yeomans and Bremner, 1988) and wet combustion with CO_2 capture method (Nelson and Sommers, 1982) were used, respectively. To perform a mathematical adjustment of the results from the different methods, a comparison among them was performed. This comparison showed a close relationship among the methods and the TOC results obtained from Mebius (Walkley–Black = 0.99173 × Mebius, $n = 6$, $r^2 = 0.99$, $P < 0.0001$) and wet combustion with CO_2 capture methods (Walkley–Black = 1.08776 × wet combustion, $n = 6$, $r^2 = 0.99$, $P < 0.0001$), which were mathematically adjusted to the Walkley–Black method. The TOC results were expressed in equivalent soil depth (Bayer et al., 2000b), where the soil bulk density was determined with soil cores sampled by volumetric rings (Embrapa, 1997).

Particulate Organic Carbon

The physical fractionation of SOM followed the procedure described by Cambardella and Elliot (1992). The C contents were determined in the >53-μm size fraction. The results of POC were expressed only at the 0- to 5-cm layer, which was the layer more affected by the NT system. Treatment effect on POC in the deeper layers followed the same trend of the 0- to 5-cm layer, but with lower magnitude (data not shown).

Calculation of Carbon Pool Indexes and Lability of Soil Organic Matter

The carbon pool index (CPI) and the particulate organic carbon pool index (POCPI) were calculated, respectively, through the ratio between TOC or POC stocks in each treatment and the TOC or POC stocks in the native grassland reference system (Blair et al., 1995; Diekow et al., 2005b). The lability of SOM was estimated through the ratio between the labile pool and the non-labile pool of SOM, where the labile pool was the POC stock and the non-labile pool was calculated by difference between TOC and POC stocks (Bayer et al., 2002; Diekow et al., 2005b).

Densimetric Fractionation of Soil Organic Matter

To evaluate the importance of physical protection on the organic C accumulation in NT soils from southern Brazil, soil surface samples (0- to 5-cm layer) of the sandy clay loam Paleudult were submitted for a densimetric fractionation of SOM (Golchin et al., 1994) using a 2.0 g cm^{-3} sodium polytungstate (SPT) solution. Ten grams of <9.5-mm soil aggregates were immersed in 80 mL of SPT in a centrifuge tube. The tube was covered with plastic and manually inverted slowly five times to avoid disruption of aggregates, and then allowed to stand for 60 min before centrifuging at 2000 × g for 90 min. After removal of light free fraction (LFF) of SOM, SPT solution was added to residual soil and the volume of the suspension adjusted and sonified using a total energy of 250 J mL^{-1} to break soil aggregates and liberate the occluded fraction (LOF) of SOM. The tube was allowed to stand for 60 min before centrifuging at 2000 × *g* for 90 min. The free and occluded fractions were obtained through filtration of the overflow, and they were washed with deionized water, dried at 60°C for 24 h, and analyzed in relation to C concentrations by dry combustion in a TOC analyzer (Shimadzu, Kyoto, Japan). These C results were not adjusted to the Walkley–Black method. As the results of LFF and LOF did not compare or relate to the TOC or POC results, they will be used only to evaluate the importance of physical protection of SOM in the NT clay loam Paleudult.

Carbon Accumulation Rates

The C accumulation rates were calculated for the 0- to 20-cm depth using the following equation:

$$\text{rate (Mg ha}^{-1}\ \text{yr}^{-1}) = (\text{TOC stock in improved system} - \text{TOC stock in traditional system})/\text{years}$$

Statistical Analysis

Analysis of variance was performed using the SAS statistical package (SAS Institute, 2001). Each field site was analyzed separately, according to experimental design. The third experiment results were analyzed according to a randomized block design, with three replications (subsamples). The Tukey test was applied at $p < 0.05$ level of probability.

RESULTS AND DISCUSSION

Total Organic Carbon and Organic Carbon in the Particulate Fraction

The TOC contents in 0- to 5- and 0- to 20-cm soil layers are shown in Table 2. The TOC in native grass was higher in clayey than in sandy soils. In the high clay Hapludox (760 g kg^{-1} of clay), the native grass had 159% higher TOC at 0 to 20 cm than in the sandy loam Paleudalf (87 g kg^{-1} of clay). In addition to its clay content, the high clay Hapludox site had a lower temperature regime than the sandy loam Paleudalf, which may have contributed to the results reported in Table 2. In addition, the clayey soils had higher nutrient availability than the sandy soils, which resulted in increased biomass production of the native grass and thus in a buildup of TOC. The observed difference of TOC stocks was also probably due to higher physical and chemical protection of organic matter in clayey soils when compared to sandy soils (Parfitt et al., 1997; Bayer et al., 2001, 2002). However, considering the lower altitude and higher temperature in Cruz Alta than Campos Novos, it is not clear why the clay Hapludox (570 g kg^{-1} of clay) from Cruz Alta showed 12.9 Mg C ha^{-1} higher TOC at 0 to 20 cm than high the clay Hapludox (760 g kg^{-1} of clay) from Campos Novos (Table 2). The most probable explanation could be related to different mineralogy of

Table 2. Effect of soil management and crop system on total organic carbon (TOC), particulate organic carbon (POC), carbon pool index (CPI), and particulate organic carbon pool index (POCPI) for four different soils of southern Brazil.

						Ratio				
Soil	**Time of adoption**	**Soil management†**	**TOC (0–5 cm)**	**POC (0–5 cm)**	**TOC (0–20 cm)**	**POC (0–5 cm) to TOC (0–5 cm)**	**TOC (0–5 cm) to TOC (0–20 cm)**	**CPI‡ (0–20 cm)**	**CPI (0–5 cm)**	**POCPI‡ (0–5 cm)**
	yr		Mg ha^{-1}							
Sandy loam Paleudalf (clay = 87 g kg^{-1})	10	bare soil	3.21b§	0.27c	14.9b	0.08	0.22	0.67	0.45	0.16
		NT fallow–maize	6.76a	1.09bc	19.2ab	0.16	0.35	0.87	0.94	0.63
		NT ryegrass–maize	8.22a	2.49ab	20.8a	0.30	0.40	0.94	1.14	1.43
		NT TLCC (velvet beans)–maize	9.42a	2.97a	25.1a	0.32	0.38	1.14	1.31	1.71
		native grass	7.18a	1.74ab	22.1a	0.24	0.32	1.00	1.00	1.00
		CV, %¶	11.3	24.2	10.6					
Sandy clay loam Paleudult (clay = 220 g kg^{-1})	15	CTWN black oat–maize	7.27c	0.82d	30.0d	0.11	0.24	0.69	0.48	0.22
		CT black oat–maize	8.47bc	1.21cd	33.8cd	0.14	0.25	0.78	0.55	0.32
		RT black oat–maize	9.27bc	1.64cd	34.2cd	0.18	0.27	0.79	0.61	0.44
		NT black oat–maize	10.47b	2.57bcd	35.6c	0.25	0.29	0.82	0.69	0.69
		NT ICS I#	14.17a	2.79bc	39.4ab	0.20	0.36	0.91	0.93	0.74
		NT TLCC (pigeon pea)–maize	16.50a	5.72a	41.3ab	0.35	0.40	0.95	1.08	1.53
		native grass	15.28a	3.75b	43.3a	0.25	0.35	1.00	1.00	1.00
		CV, %	8.0	23.4	7.6					
Clay Hapludox (clay = 570 g kg^{-1})	19	CT wheat–soybean	12.5d	1.29c	48.7d	0.10	0.26	0.69	0.57	0.29
		CT ICS II#	13.4d	1.72c	53.6c	0.13	0.25	0.76	0.61	0.39
		NT wheat–soybean	16.2c	3.02b	51.8cd	0.19	0.31	0.74	0.74	0.68
		NT ICS II	18.0b	3.23b	58.3b	0.18	0.31	0.83	0.82	0.73
		native grass	22.0a	4.41a	70.1a	0.20	0.31	1.00	1.00	1.00
		CV, %	6.3	20.7	3.9					
High clay Hapludox (clay = 760 g kg^{-1})	7	CT ICS III# residue removed	11.9b	3.26b	47.8b	0.27	0.25	0.84	0.53	0.30
		CT ICS III	14.0ab	3.81b	50.4b	0.27	0.28	0.88	0.62	0.35
		NT ICS III	15.9ab	5.40b	53.4ab	0.34	0.30	0.93	0.70	0.50
		native grass	22.6a	10.83a	57.2a	0.48	0.40	1.00	1.00	1.00
		CV, %	29.7	23.2	8.1					

† CT, conventional tillage; CTWN, conventional tillage without nitrogen fertilization; NT, no tillage; RT, reduced (chisel) tillage; TLCC, tropical legume cover crop.

‡ CPI = TOC treatment/TOC native grass; POCPI = POC treatment/POC native grass.

§ Means followed by same letter within a column, into the same field site, do not differ by Tukey test at the α = 0.05 level.

¶ Coefficient of variation.

Intensive Cropping System (ICS) I = black oat + common vetch–maize + cowpea. ICS II = black oat–soybean–black oat + vetch–maize–radish oil–wheat–soybean. ICS III = triticale–rye–soybean–common vetch–maize–black oat–black bean–buck wheat–radish oil.

these soils or different botanic composition of native vegetation between the two sites.

The effect of soil texture on TOC also can be evaluated comparing similar soil management systems among different soil types. Despite the lower annual additions of crop residue (Table 3), the wheat–soybean under CT in clay Hapludox (570 g kg^{-1} of clay) had 44% higher TOC (0- to 20-cm layer) than black oat–maize under CT in sandy clay loam Paleudult (220 g kg^{-1} of clay). Similarly, the wheat–soybean under NT in clay Hapludox had 46% higher TOC (0- to 20-cm layer) than in black oat–maize under NT in sandy clay loam Paleudult, despite the lower annual crop residue addition in the first soil.

In NT, the use of tropical legume cover crops (velvet beans in sandy loam Paleudalf and pigeon pea in sandy clay loam Paleudult) in maize cropping systems and Intensive Cropping Systems I (black oat + common vetch–maize + cowpea) and II (black oat–soybean–black oat + vetch–maize–radish soil–wheat–soybean), maintained by crop rotation and cover crops, were able to maintain the TOC stock statistically similarly to the reference treatment (native grass). Therefore, NT performance was improved by the high inputs of biomass C and N, via biologic fixation and mineral N fertilization, accomplished in the more intensive and diversified cropping systems (Burle et al., 1997; Bayer et al., 2002; Freixo et al., 2002; Sisti et al., 2004; Diekow et al., 2005a). Conversely, under CT, regardless of cropping system and soil type, there was a decrease in TOC when compared to native grass. However, this decrease was more pronounced in the soils with lower clay content.

The soil management systems modified the ratio of TOC (0- to 5-cm layer) to TOC (0- to 20-cm layer) verified in native grass (Table 2). Conventionally tilled soil had a decrease in this ratio, showing that the distribution of TOC in the soil profile under CT was more uniform than in native grassland soil, most likely due to the annual soil disturbance and deposition of residue into the soil tillage layer. Except for the high clay Hapludox, the NT soils that were combined with intensive cropping systems and systems with tropical legume cover crops were able to maintain or even increase this ratio compared to native grass, which is related to preferential C accumulation on the soil surface where the crop residues are placed.

Particulate organic carbon (POC), mainly composed of crop residues and roots in initial decomposition stages, has been considered as a more sensitive indicator of soil management than TOC (Bayer et al., 2001, 2002; Conceição and Amado, 2002). The carbon pool index (CPI) proposed by Blair et al. (1995) was calculated to the 0- to 5- and 0- to 20-cm depths and adapted to particulate organic carbon (POCPI). These indexes comparing the highest (improved soil management system) and the lowest (poor soil management system) TOC soil management treatments for each soil were the following: sandy loam Paleudalf, 2.9 and 10.7; sandy clay loam Paleudult, 2.3 and 7.0; and high clay Hapludox, 1.3 and 1.7, respectively, for CPI and POCPI. These results show that POCPI was a more sensitive indicator for soil management than CPI, regardless of the soil type. The highest CPIs were found in intensive cropping systems and with tropical legume cover crops under NT; on the other hand, the lowest CPIs were found in the treatments with the combination of absent or low biomass input and CT. The effect of soil management on POCPI has consequences for soil quality due to the role of this labile organic C fraction in nutrient cycling, biologic activity, and many related soil properties (Blair et al., 1995; Diekow et al., 2005b). In the highest clay content soil, the CPI (0- to 20-cm layer) showed low sensitivity to soil management, while CPI (0- to 5-cm layer) and POCPI were able to discriminate among the soil management systems. Generally, POC had a higher coefficient of variation than TOC, except for the high clay Hapludox (Table 2).

Table 3. Carbon and nitrogen input to the soil in the management systems.

Soil	Soil management†	Mineral N fertilizer‡	Aboveground C input	Total N input§
		kg ha^{-1}	Mg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}
Sandy loam Paleudalf	bare soil	0	0	0
	NT fallow–maize	130	2.78	130
	NT ryegrass–maize	130	3.76	130
	NT TLCC (velvet beans)–maize	65	4.51	165
Sandy clay loam Paleudult	CTWN black oat–maize	0	4.24	0
	CT black oat–maize	144	6.67	144
	RT black oat–maize	144	7.09	144
	NT black oat–maize	144	6.63	144
	NT ICS I¶	144	7.83	244
	NT TLCC (*pigeon pea*)–*maize*	144	6.84	344
Clay Hapludox	CT wheat–soybean#	73	3.67	73
	CT ICS II¶	48	5.18	74
	NT wheat–soybean#	73	4.03	73
	NT ICS II	48	5.87	78
High clay Hapludox	CT ICS III¶ residue removed	64	0.66	70
	CT ICS III	64	3.77	90
	NT ICS III	64	3.43	90

† CT, conventional tillage; CTWN, conventional tillage without nitrogen fertilization; NT, no tillage; RT, reduced (chisel) tillage; TLCC, tropical legume cover crop.

‡ Nitrogen source was urea.

§ Total nitrogen input = mineral N fertilizer + N addition in aboveground legume cover crop.

¶ Intensive Cropping System (ICS) I = black oat + common vetch–maize + cowpea. ICS II = black oat–soybean–black oat + vetch–maize–radish oil–wheat–soybean. ICS III = triticale–rye–soybean–common vetch–maize–black oat–black bean–buck wheat–radish oil.

Soybean was considered as a neutral N balance due to high grain exportation.

The treatments with tropical legume cover crops such as pigeon pea–maize (sandy clay loam Paleudult) and velvet beans–maize (sandy loam Paleudalf) had, respectively, 53 and 71% higher POC stocks than the native grass treatment. Good soil management practices, such as cover crops, minimum soil disturbance, N fertilization, and legume cover crops increased POC stocks. In contrast, in the sandy clay loam Paleudult, the POC stocks under double-cropping systems (black oat–maize) with RT and CT reached only 56 and 68%, respectively, of the reference treatment. These results indicate that treatments with improved soil management practices increase POC stocks and treatments with poor soil management promote decrease of this C fraction in relation to native grass (Table 2).

The lability of SOM, calculated as the ratio between POC and TOC stocks at 0 to 5 cm, varied from 0.20 to 0.48 in soils under native grass. The management systems that combined low crop residue addition and intensive soil disturbance (CT) led to a decrease in SOM lability (POC to TOC ratio varying from 0.08 to 0.27). In contrast, NT soils with high addition of crop residues promoted an increase in the SOM lability as evidenced by the higher POC to TOC ratios (varying from 0.18 to 0.35). Lability is an important property of SOM because it affects the fluxes of C and energy in soil through microbial activity, which, in turn, provides a positive feedback on soil quality (Blair et al., 1995; Conceição and Amado, 2002; Diekow et al., 2005b).

Rates of Carbon Accumulation

Tillage Effect

The NT soils showed a range of 0.12 to 0.43 Mg C ha^{-1} yr^{-1} of C accumulation relative to the CT soil (Table 4). In the sandy clay loam Paleudult, NT had 0.12 Mg ha^{-1} yr^{-1} C higher accumulation than CT under the double-cropping system (black oat–maize). In this soil, the TOC increment rates were 26.7 (0- to 5-cm layer) and 6.0 (0- to 20-cm layer) kg ha^{-1} cm^{-1} yr^{-1}, indicating that C accumulation in the NT soils occurred preferentially in soil surface layer.

In the clay Hapludox, NT had 0.16 Mg ha^{-1} yr^{-1} of C accumulation compared to CT, with both under double-cropping system (wheat–soybean). The TOC increment rates were 39.0 (0- to 5-cm layer) and 8.0 (0- to 20-cm layer) kg ha^{-1} cm^{-1} yr^{-1}. The similar rate of NT C accumulation in the clay Hapludox (0.16 Mg ha^{-1} yr^{-1}) in comparison to sandy clay loam Paleudult (0.12 Mg ha^{-1} yr^{-1}) probably is related to higher C addition in the sandy clay loam Paleudult than in clay Hapludox (Table 3), which partly compensates for the lower C stabilization in the Paleudult.

The highest rates of C accumulation in NT compared to CT were found when the intensive cropping systems replaced the traditional double-cropping system used in southern Brazil. In the clay Hapludox soil NT had 0.25 Mg ha^{-1} yr^{-1} more C accumulation than CT under Intensive Cropping System II. There was an increase of 56% in NT C accumulation rate due to the more intensive in cropping system. The TOC increment rates were 48.4 (0- to 5-cm layer) and 12.5 (0- to 20-cm layer) kg ha^{-1} cm^{-1} yr^{-1}.

In the high clay Hapludox, the NT had 0.43 Mg ha^{-1} yr^{-1} more C accumulation than CT under Intensive Cropping System III. The TOC increment rates were 54.3 (0- to 5-cm layer) and 21.5 (0- to 20-cm layer) kg ha^{-1} cm^{-1} yr^{-1}. Therefore, the C accumulation rates of NT compared to CT under an intensive cropping system were greater in the high clay Hapludox than in the clay Hapludox (0.25 Mg ha^{-1} yr^{-1}). Considering the lower crop residue additions in the high clay Hapludox than in the clay Hapludox (Table 3), higher rates of C accumulation in the high clay soil are most likely be related to

Table 4. Effects of soil management and crop system on annual rate of carbon accumulation in four different soil types from southern Brazil.

Soil	Clay content	Time of adoption	Crop system	TOC† (0–20 cm) CT†	TOC† (0–20 cm) NT†	Carbon accumulation: Tillage effect	Carbon accumulation: Cropping effect	Carbon accumulation: Tillage and cropping effect
	$g\ kg^{-1}$	yr		$Mg\ ha^{-1}$		$Mg\ ha^{-1}\ yr^{-1}$		
Sandy loam Paleudalf	87	10	mono-cropping (fallow–maize)	–	19.2	–	–	–
			double-cropping (ryegrass–maize)	–	20.8	–	0.43 (TLCC × double-cropping under NT)	
			TLCC‡ (velvet beans–maize)	–	25.1	–	0.59 (TLCC × mono-cropping under NT)	–
Sandy clay loam Paleudult	220	15	double-cropping (black oat–maize)	33.8	35.6	0.12 (NT × CT under double-cropping)	–	–
			ICS I§	–	39.4	–	0.25 (intensive × double-cropping under NT)	0.37 (NT intensive × CT double-cropping)
			TLCC (pigeon pea–maize)		41.3		0.38 (TLCC × double-cropping under NT)	
Clay Hapludox	570	19	double-cropping (wheat–soybean)	48.7	51.8	0.16 (NT × CT under double-cropping)	0.26 (intensive × double-cropping under CT)	–
			ICS II§	53.6	58.3	0.25 (NT × CT under ICS II)	0.34 (intensive × double-cropping under NT)	0.51 (NT intensive × CT double-cropping)
High clay Hapludox	760	7	ICS III§	50.4	53.4	0.43 (NT × CT under ICS III)	–	–

† TOC, total organic carbon; CT, conventional tillage; NT, no-tillage.

‡ TLCC, tropical legume cover crop.

§ Intensive Cropping System (ICS) I = black oat + common vetch–maize + cowpea. ICS II = black oat–soybean–black oat + vetch–maize–radish oil–wheat–soybean. ICS III = triticale–rye–soybean–common vetch–maize–black oat–black bean–buck wheat–radish oil.

the shorter duration of the experiment (7 yr) compared to the clay soil (19 yr). Higher C accumulation rates are expected to occur in the first couple years of NT adoption in SOM-depleted soils.

Cropping System Effect

The highest rate of C accumulation (0.59 Mg ha^{-1} yr^{-1}) was found in the velvet beans (tropical legume cover crop)–maize system compared to winter fallow–maize under NT, in the sandy loam Paleudalf (Table 4). The TOC increment rates were 53.2 (0- to 5-cm layer) and 29.5 (0- to 20-cm layer) kg ha^{-1} cm^{-1} yr^{-1}. No-till with tropical legume increased C accumulation compared to double-cropping system (rye–maize) by 0.43 Mg ha^{-1} yr^{-1}. However, it should be stressed that the sandy loam Paleudalf had the lowest TOC stocks among the soils investigated.

In the sandy clay loam Paleudult the pigeon pea (tropical legume cover crop)–maize had 0.38 Mg ha^{-1} yr^{-1} more C accumulation than the black oat–maize (double-cropping system) in NT. The TOC increment rates were 80.4 (0- to 5-cm layer) and 19.0 (0- to 20-cm layer) kg ha^{-1} cm^{-1} yr^{-1}. The C accumulation rate in the sandy loam Paleudalf under NT was 55% higher than in sandy clay loam Paleudult, which must be related to the different reference systems used (winter fallow in sandy loam Paleudalf and black oat in the sandy clay loam Paleudult). In both cropping systems under NT, the highest gain of C was verified in the shallow soil layer. The tropical legume cover crops provide high inputs of C and N from aboveground biomass and roots. Also, the following maize crop is expected to produce higher biomass due to improvement in N soil availability from the previous legume cover crop (Amado et al., 2001; Bayer et al., 2000a, 2000b, 2006a; Diekow et al., 2005a).

The NT rate of C accumulation in the intensive cropping system compared to double-cropping system was higher in the clay Hapludox (0.34 Mg ha^{-1} yr^{-1}) than in the sandy clay loam Paleudult (0.25 Mg ha^{-1} yr^{-1}). This result is likely related to the increased stability of the SOM in the clay soil when compared to sandy clay loam, despite the lower additions of plant biomass to the clay Hapludox. Under NT, the difference in C addition between an intensive cropping system and double-cropping system was greater in the clay Hapludox (1.84 Mg C ha^{-1} yr^{-1}) than in sandy clay loam Paleudult (1.20 Mg C ha^{-1} yr^{-1}) (Table 3). Also, the study on the clay Hapludox was performed for 4 yr longer than on the sandy clay loam Paleudult.

The lowest C accumulation rates across cropping systems were verified under CT. For example, in the clay Hapludox, the Intensive Cropping System II under CT experienced a C increase rate of 0.26 Mg ha^{-1} yr^{-1} higher rate of C accumulation than the double-cropping system. Under NT, the difference extended to 0.34 Mg C ha^{-1} yr^{-1}. The smaller C accumulation observed under CT in the clay Hapludox is related to the smaller C additions observed under this system (Table 3). The TOC increment rates for CT were 9.5 (0- to 5-cm layer) and 12.9 (0- to 20-cm layer) kg ha^{-1} cm^{-1} yr^{-1}. There was a slight increase in soil C storage under CT when the cropping system was improved. The approximately uniform increment in C through the soil depths probably is related to use of a plow disc and tandem disc in CT system. These disc implements promote a more uniform distribution of residues through the soil profile than the moldboard plow, which inverts the soil layers, or NT, which keeps the residues on soil surface (Sá et al., 2001).

Tillage and Cropping Effect

In the sandy clay loam Paleudult, NT under Intensive Cropping System I (four crops yr^{-1}) had a C addition rate of 7.83 Mg ha^{-1} yr^{-1} compared to 6.67 Mg ha^{-1} yr^{-1} for CT under double-cropping (two crops yr^{-1}) (Table 3). The NT under Intensive Cropping System I on the sandy clay loam Paleudult had an annual C accumulation rate that was 0.37 Mg ha^{-1} yr^{-1} higher than for CT under double cropping. This rate is approximately three times higher than the rate found when comparing NT to CT alone (0.12 Mg ha^{-1} yr^{-1}). It should be stressed that in this case there are two effects combined: minimum soil disturbance provide by NT and higher residue addition due to the Intensive Cropping System I. The TOC increment rates, comparing NT under Intensive Cropping System I with CT under double-cropping system in the sandy clay loam Paleudult, were 76.0 (0- to 5-cm layer) and 18.5 (0- to 20-cm layer) kg ha^{-1} cm^{-1} yr^{-1}. Carbon accumulation was approximately four times higher in the first than the second soil depth.

In the clay Hapludox, the Intensive Cropping System II under NT had a C accumulation of 0.51 Mg ha^{-1} yr^{-1} higher than the double-cropping system under CT. The difference in annual C inputs between these two systems was 2.20 Mg ha^{-1} yr^{-1} of C in favor of the Intensive Cropping System II under NT (Table 3). In general, the combined use of NT and an intensive cropping system resulted in higher C accumulation rates. The single effect of tillage under an intensive cropping system (NT × CT = 0.25 Mg ha^{-1} yr^{-1}) was lower than the single effect of a cropping system under NT (Intensive Cropping System II × double-cropping = 0.34 Mg ha^{-1} yr^{-1}). Thus, under an intensive cropping system, NT had 0.69 Mg ha^{-1} yr^{-1} more C addition than CT in the same cropping system. The intensive cropping system had 1.84 Mg ha^{-1} yr^{-1} more C addition than the double-cropping system, both under NT (Table 3). These results stress the importance of crop residue addition to enhance the potential of C sequestration in NT soils.

Physical Protection of Organic Matter in Tillage Systems

The densimetric fractionation of SOM was performed at the 0- to 5-cm soil depth in the sandy clay loam Paleudult to evaluate the effect of the physical protection on C accumulation in this southern Brazil soil. Figure 2 shows the effect of NT on C stocks in the free and occluded light fractions of SOM in comparison to CT soil. It was observed that the C stock in the free light fraction was 3.5 times higher in NT than CT soil. This result was probably a consequence of the decrease in

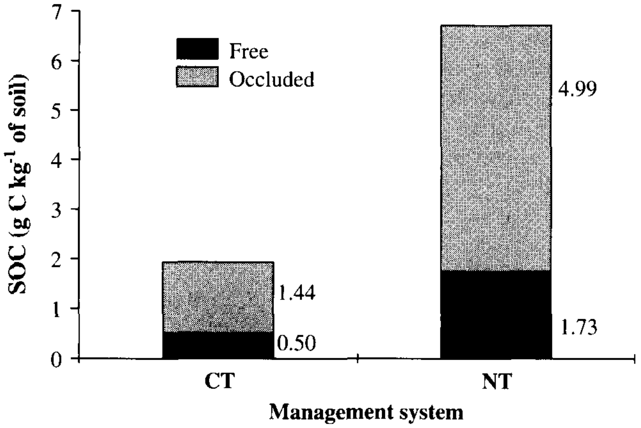

Fig. 2. Free and occluded light fractions of soil organic carbon (SOC) at the 0- to 5-cm depth of the sandy clay loam Paleudult under conventional tillage (CT) and no-till (NT) systems.

soil temperature mainly in the surface layers, and lower residue–soil contact in NT compared to CT. The NT also increased by 3.5 times the C stock in the occluded fraction in comparison to CT. These tillage systems did not change the proportion of free and occluded fraction in TOC. In addition, the increase of C stock in the occluded light fraction of SOM (3.55 g C kg^{-1} of soil) represented approximately 74% of the total increase in the light fraction (4.78 g C kg^{-1} of soil) observed under NT relative to CT. These results suggest that physical protection of organic matter into soil aggregates was an important mechanism in the increase of C stocks in the NT sandy clay loam Paleudult (subtropical soil). These results were similar to those obtained in temperate soils (Carter et al., 1994; Franzluebbers and Arshad, 1997; Six et al., 2000). The importance of physical protection to C accumulation in NT soils also depends on soil texture and mineralogy, effects that need to be better understood in tropical and subtropical soils.

CONCLUSIONS

Carbon accumulation in NT soils occurred mainly in soil surface layers, and the highest rates were obtained by the combination of NT with tropical summer legume cover crops in maize systems, followed by the intensive crop rotation systems. In general, soil C stocks in native grass sites had a close relationship with soil clay content. In contrast, soil texture had no clear effect on C accumulation rates under conservative soil management systems. The increase in C and N inputs from crop residue resulted in an increase in soil C accumulation, and this effect was more pronounced under NT than CT. The particulate organic C was more sensitive than total organic C in distinguishing soil management systems. There was an increase of the C lability in soils under NT compared to conventionally tilled soils. Physical protection of SOM was evidenced as an important mechanism of organic C accumulation in NT in the sandy clay loam Paleudult. Further studies evaluating different soil types are needed in Brazil cropping systems to confirm the role of this mechanism in the stabilization of SOM, as well to evaluate the effect of soil texture and mineralogy on the C accumulation rates under NT.

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REFERENCES

Amado, T.J.C., C. Bayer, F.L.F. Eltz, and A.C.R. Brum. 2001. Potencial de culturas de cobertura em acumular carbono e nitrogênio no solo no plantio direto e a melhoria da qualidade ambiental. Rev. Bras. Cienc. Solo 25:189–197.

Baldock, J.A., and J.O. Skjemstad. 2000. Role of the matrix and minerals in protecting natural organic materials against biological attack. Org. Geochem. 31:697–710.

Balesdent, J., C. Chenu, and M. Balabane. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53:215–230.

Bayer, C., L. Martin-Neto, J. Mielniczuk, and C.A. Ceretta. 2000a. Effect of no-till cropping systems on soil organic matter in a sandy clay loam Acrisol from southern Brazil monitored by electron spin resonance and nuclear magnetic resonance. Soil Tillage Res. 53: 95–104.

Bayer, C., L. Martin-Neto, J. Mielniczuk, J. Diekow, and T.J.C. Amado. 2006a. C and N stocks and the role of molecular recalcitrance and organomineral interaction in stabilizing soil organic matter in a subtropical Acrisol managed under no-tillage. Geoderma (in press).

Bayer, C., L. Martin-Neto, J. Mielniczuk, and S. Langoi. 2001. Changes in soil organic matter fractions under subtropical no-till cropping systems. Soil Sci. Soc. Am. J. 65:1473–1478.

Bayer, C., L. Martin-Neto, J. Mielniczuk, A. Pavinato, and J. Diekow. 2006b. Carbon sequestration in two Brazilian Cerrado soils under no-till. Soil Tillage Res. 86:237–245.

Bayer, C., J. Mielniczuk, T.J.C. Amado, L. Martin-Neto, and S.V. Fernandes. 2000b. Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in southern Brazil. Soil Tillage Res. 54:101–109.

Bayer, C., J. Mielniczuk, L. Martin-Neto, and P.R. Ernani. 2002. Stocks and humification degree of organic matter fractions as affected by no-tillage on a subtropical soil. Plant Soil 238:133–140.

Blair, G.J., R.D.B. Lefroy, and L. Lisle. 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46:1459–1466.

Burle, M.L., J. Mielniczuk, and S. Fochi. 1997. Effect of cropping systems on soil chemical characteristics, with emphasis on soil acidification. Plant Soil 190:309–316.

Cambardella, C.A., and E.T. Elliot. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777–783.

Campos, B.C. 2005. Balanço do carbono em sistemas de manejo do solo e culturas. Prova de Qualificação, PPGCS, Santa Maria, RS, Brazil.

Campos, B.C., D.J. Reinert, R. Nicolodi, J. Ruedel, and C. Petrere. 1995. Estabilidade estrutural de um latossolo vermelho escuro após sete anos de rotação de culturas e sistemas de manejo de solo. Rev. Bras. Cienc. Solo 19:121–126.

Carter, M.R., D.A. Angers, and H.T. Kunelius. 1994. Soil structure and organic matter fractions under perennial grasses. Soil Sci. Soc. Am. J. 58:1194–1199.

Conceição, P.C. 2002. Indicadores de qualidade do solo visando a avaliação de sistemas de manejo do solo. Tese de Mestrado. Universidade Federal de Santa Maria, RS, Brazil.

Conceição, P.C., and T.J.C. Amado. 2002. Qualidade do solo sob sistema plantio direto em dois experimentos de longa duração no Rio Grande do Sul. Rev. Plantio Direto 72:29–33.

Diekow, J., J. Mielniczuk, H. Knicker, C. Bayer, D.P. Dick, and I.

Kögel-Knabner. 2005a. Soil C and N stocks as affected by cropping systems and nitrogen fertilization in a southern Brazil Acrisol managed under no-tillage for 17 years. Soil Tillage Res. 81:87–95.

Diekow, J., J. Mielniczuk, H. Knicker, C. Bayer, D.P. Dick, and I. Kögel-Knabner. 2005b. Carbon and nitrogen stocks in physical fractions of a subtropical Acrisol as influenced by long-term no-till cropping systems and N fertilization. Plant Soil 268:319–328.

Embrapa. 1997. Manual de métodos de análises de solo. 2nd ed. Ministério da Agricultura e do Abastecimento, Rio de Janeiro, RJ, Brazil.

Feller, C., and M.H. Beare. 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69–116.

Franzluebbers, A.J., and M.A. Arshad. 1997. Particulate organic carbon content and potential mineralization as affected by tillage and texture. Soil Sci. Soc. Am. J. 61:1382–1386.

Freixo, A.F., P.L.O.A. Machado, H.P. Santos, C.A. Silva, and F.S. Fadigas. 2002. Soil organic and fractions of Rhodic Ferralsol under the influence of tillage and crop rotation systems in southern Brazil. Soil Tillage Res. 64:221–230.

Gianluppi, D., I. Scopel, and J. Mielniczuk. 1979. Alguns prejuízos da erosão do solo no RS. p. 92. *In* Congresso Brasileiro de Ciência do Solo, XVII, Manaus. Resumos. SBCS, Campinas, SP, Brazil.

Golchin, A., J.M. Oades, J.O. Skjemstad, and P. Clarke. 1994. Study of free and occluded particulate organic matter in soil by solid state 13C CP/MAS NMR spectroscopy and scanning electron microscopy. Aust. J. Soil Res. 32:285–309.

Hassink, J., and A. Whitmore. 1997. A model of the physical protection of organic matter in soils. Soil Sci. Soc. Am. J. 61:131–139.

Koeppen, W. 1948. Climatologia: Con un estudio de los climas de la tierra. Fondo de Cultura Economica, México.

Lal, R., R.F. Follet, J. Kimble, and C.V. Cole. 1999. Managing U.S. cropland to sequester carbon in soil. J. Soil Water Conserv. 54:374–381.

Lovato, T., J. Mielniczuk, C. Bayer, and F. Vezzani. 2004. Adição de carbono e nitrogênio e sua relação com os estoques no solo e com o rendimento do milho em sistemas de manejo. Rev. Bras. Cienc. Solo 28:175–187.

Mielniczuk, J. 2003. Manejo do solo no Rio Grande do Sul: Uma síntese histórica. p. 5–14. *In* Curso de Fertilidade do Solo em Plantio Direto, VI. Passo Fundo, Resumo de palestras. Aldeia Norte Editora Ltda., Ibirubá, RS, Brazil.

Mielniczuk, J., C. Bayer, F.M. Vezzani, T. Lovato, F.F. Fernandes, and L. Debarba. 2003. Manejo de solo e culturas e sua relação com os estoques de carbono e nitrogênio do solo. p. 209–248. *In* N. Curi et al. (ed.) Tópicos em Ciência do solo 3. Sociedade Brasileira de Ciência do Solo, Viçosa, MG, Brazil.

Nelson, P.W., and C.E. Sommers. 1982. Total C, organic C and organic matter. p. 539–579. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Parfitt, R.L., B.K.G. Theng, J.S. Whitton, and T.G. Shepherd. 1997. Effects of clay minerals and land use on organic matter pools. Geoderma 75:1–12.

Sá, J.C.M., C.C. Cerri, W.A. Dick, R. Lal, S.P. Venske-Filho, M.C. Piccolo, and B.E. Feigl. 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. Soil Sci. Soc. Am. J. 65:1486–1499.

SAS Institute. 2001. SAS user's guide: Statistics. Version 8.2. 6th ed. SAS Inst., Cary, NC.

Sisti, C.P.J., H.P. Santos, R. Kohhann, B.J.R. Alves, S. Urquiaga, and R.M. Boddey. 2004. Change in carbon and nitrogen stocks in soil under 13 years of conventional and zero tillage in southern Brazil. Soil Tillage Res. 76:39–58.

Six, J., E.T. Elliot, and K. Paustian. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63:1350–1358.

Six, J., E.T. Elliot, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32:2099–2103.

Six, J., E.T. Elliot, K. Paustian, and J.W. Doran. 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62:1367–1377.

Soil Survey Staff. 1999. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd ed. Agric. Handb. 436. USDA-NRCS, Washington, DC.

Spagnollo, E. 2004. Dinâmica da matéria orgânica em agroecossistemas submetidos a queima e manejo dos resíduos culturais. Tese de doutorado. Universidade Federal de Santa Maria, RS, Brazil.

Veiga, M., C.M. Pandolfo, and L.P. Wildner. 2000. Sistemas de manejo de resíduos de colheita associados à aplicação de fontes de nutrientes: I. Alterações em algumas características químicas do solo. p. 287–293. *In* IV Encontro Latino-Americano sobre Plantio direto na Pequena Propriedade, Anais. EMATER-RS/ASCAR, Porto Alegre, RS, Brazil.

Walkley, A., and L.A. Black. 1947. Determination of organic matter in the soil by chromic acid digestion. Soil Sci. 63:251–264.

Yeomans, J.C., and J.M. Bremner. 1988. A rapid and precise method for routine determination of organic carbon in soil. Commun. Soil Sci. Plant Anal. 19:1467–1476.

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